LONG PERIOD VARIATIONS IN TIDAL AND LIBRATIONAL FORCING OF EUROPA

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Introduction: The gravitational field of Jupiter exerts a profound influence on the energy balance, thermal evolution, and stress regime of Europa. It is widely appreciated that dissipation associated with the spheroidal tidal deformation is a major source of heat [1, 2, 3, 4]. Another possibly important source of dissipation is the toroidal deformation field associated with forced librations [5, 6, 7]. Both tidal and librational deformations depend on the distance and direction to Jupiter, as seen from Europa. These quantities vary with time as a result of the finite values of orbital eccentricity and spin pole obliquity, though the obliquity effects have been ignored in most previous studies.

Variations in eccentricity and obliquity of the Galilean satellites occur on a very wide range of time scales, as angular momentum is exchanged among the orbital and rotational components of the coupled system. The orbital periods are only a few days in length, and the secular changes in orbital period associated with tidal and librational dissipation have characteristic time scales of 10^9 years or longer [8, 9, 10]. On intermediate time scales, the satellites perturb each other, and the Sun and Saturn make additional contributions.

The present values of satellite orbital inclinations and obliquities are not particularly representative of their respective longer term variations. As a result, the tidal stress and dissipation regimes at present may not provide adequate explanation of the sources of surface features seen on the satellites.

Obliquity: On relatively short time scales ($<10^4$ years), the satellite inclinations and obliquities can be approximated by a model which treats the spin pole of Jupiter as inertially fixed. In that case, each satellite orbit plane responds to torques from the oblate figure of Jupiter, mutual interaction with the other satellites, and a weak solar torque. The free oscillation periods of this system are (7.358, 29.63, 139.97, and 547.89) years. Motions of the satellite spin poles are driven by torques from Jupiter, acting on the oblate figures of the satellites. The spin pole precession periods are (0.66, 5.16, 31.9, and 320) years for Io, Europa, Ganymede and Callisto, respectively.

In order to understand longer term variations in forced obliquities of the Galilean satellites, and the resulting variations in tidal forcing, we have investigated the response of the system composed of four satellite orbits and the spin of Jupiter to varying solar torques. The solar torque varies as the orbital inclination of Jupiter varies, on time scales of 10^5-10^6 years. The dominant source of orbital variation is exchange of angular momentum between the orbits of Jupiter, Saturn, Uranus, and Neptune. In the secular variation model of Laskar [11] there are 50 Fourier terms representing the orbit pole of Jupiter.

The response of each of the objects (Jupiter's spin and satellite orbits) is a weighted sum of normal mode responses, with weights proportional to the forcing amplitude but also determined by proximity of the forcing period to the normal mode period. The free oscillation periods of the 5-body system are (7.365, 29.635, 139.56, 546.16, and 536,500) years. The spin pole precession period of Jupiter, without satellites, would be 980 kyr, but solar torques on the satellite orbits, coupled to Jupiter via its oblateness, shorten that period to 536 kyr. The largest source of uncertainty in this estimate is the polar moment of inertia of Jupiter, which has a 4% uncertainty.

One of the larger terms in Laskar's secular orbital model is nearly in resonance with the lowest frequency term in the 5-body system. This allows substantial variations in the obliquity of Jupiter and the satellite orbital inclinations on 10^5 year time scales. As the satellite orbits evolve under tidal influence, the strength of resonant forcing will vary.

Eccentricity: A similar secular variation model can be applied to estimate changes in orbital eccentricity within the Galilean satellite system. The principle difference is that mean motion resonances among the satellites pump up the eccentricity values and increase the rates of apsidal advance. The free oscillation periods of this system are (6.121, 21.21, 138.35, and 535.84) years [12]. As was seen above for the spin and orbit poles, the eccentricities are also subject to longer period perturbations associated with changes in the orbit of Jupiter.

If the only mechanisms at work were a competition between tidal dissipation, which tends to circularize orbits, and mean motion resonances, which increases eccentricity, then a steady state could conceivably be achieved, or oscillations might arise from the feedback between dissipation rate and internal heating [13]. In that case, the only interesting time scales would be the orbital periods of the satellites (a few days) and the heat transport time across the lithospheric thermal

boundary layer (highly uncertain, but likely millions of years) [13,14,15].

The presence of dynamical forcing at intermediate time scales of 10^1-10^2 years (from mutual perturbations of the satellite orbits) and 10^4-10^6 years (from changes in the orbit of Jupiter), suggests that formation of surface features on Europa might occur on some of these longer time scales.

Tides and Librations: An arbitrary displacement field in an incompressible material can be uniquely expressed as a sum of spheroidal and toroidal components. In an isotropic body, tidal deformation is purely spheroidal and that due to differential libration is purely toroidal.

The source of tidal dissipation is the stress and strain rate induced by changes in the gravitational potential at Europa as the distance and direction from Europa to Jupiter change over an orbital period, due to finite orbital eccentricity [1, 2, 3] and obliquity [16]. The ultimate source of librational dissipation is radial variation in the amplitude of forced librations [5, 6, 7], or small departures from steady rotation, which arise from torques exerted by Jupiter on the tidally deformed body of Europa.

The spatial patterns of dissipative heating and near-surface stress associated with tides and librations depend on both the internal structure of the body and on the external forcing. Simplistic models of the external forcing may lead to erroneous inferences about internal structure from observed surface features.

Cycloidal fractures may be due to tides (and/or librations) without being formed in a single orbit [17, 18]. Likewise, many other tectonic features attributed to non-synchronous rotation [19, 20, 21] may have an origin related to shorter period cycles of stress and strain.

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